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**Quantifying and Improving International Space Station
Survivability Following Orbital Debris Penetration**

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QUANTIFYING AND IMPROVING INTERNATIONAL SPACE STATION SURVIVABILITY FOLLOWING ORBITAL DEBRIS PENETRATION

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ABSTRACT

The increase of the orbital debris environment in low-earth orbit has prompted NASA to develop analytical tools for quantifying and lowering the likelihood of crew loss following orbital debris penetration of the International Space Station (ISS). NASA uses the Manned Spacecraft and Crew Survivability (MSCSurv) computer program to simulate the events that may cause crew loss following orbital debris penetration of ISS manned modules, including

- (1) critical cracking (explosive decompression) of the module,
- (2) critical external equipment penetration (such as hydrazine and high pressure tanks)
- (3) critical internal system penetration (guidance, control, and other vital components)
- (4) hazardous payload penetration (furnaces, pressure bottles, and toxic substances)
- (5) crew injury (from fragments, overpressure, light flash, and temperature rise),
- (6) hypoxia from loss of cabin pressure, and
- (7) thrust from module hole causing high angular velocity (occurring only when key Guidance, Navigation, and Control [GN&C] equipment is damaged) and , thus,

preventing safe escape vehicle (EV) departure.

MSCSurv is also capable of quantifying the "end effects" of orbital debris penetration, such as the likelihood of crew escape, the probability of each module depressurizing, and late loss of station control. By quantifying these effects (and their associated uncertainties), NASA is able to improve the likelihood of crew survivability following orbital debris penetration due to improved crew operations and internal designs.

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OBJECTIVE

The increase in man-made debris in low-earth orbit (LEO) has prompted NASA to seek new, highly accurate methods for modeling orbital debris hypervelocity impacts on spacecraft. Although debris impacts to the International Space Station (ISS) manned modules can cause serious and expensive damage, not all impacts cause penetrations, and not all penetrations lead to the death of one or more crewmembers. NASA desires to implement its goal of maximizing crew safety by computing the likelihood of loss from orbital debris penetration, and by identifying alternative internal ISS designs and crew procedures that reduce that likelihood. To help achieve this goal, NASA Marshall Space Flight Center (MSFC) contracted with the University of Denver Research Institute (DRI) to develop and use a computer code to model impacts and to quantify damage severe enough to cause deaths.

Our objectives in the analyses performed in early 2001 were:

- (1) To quantify the parameter R , the probability of loss given a penetration, and its two-sigma upper and lower bounds for individual ISS modules, for Assembly Stage 12A,
- (2) To examine how R is affected by the smaller volumes, shorter crew protocols, and other features of earlier assembly configurations,
- (3) To use predicted R factors in conjunction with the probability of no penetration (PNP) results from NASA Johnson Space Center (JSC) to estimate probabilities of no loss (PNL) for the Stage 12A configuration, and
- (4) To examine the effect of alternative crew operations on reducing R factors.

In addition to meeting these objectives, we recently refined the MSCSurv program and associated data files to better model external and internal equipment and crew operational protocols. These code improvements and insights should result in more accurate prediction of R factors and in improved safety of operations following orbital debris penetration of the International Space Station manned modules.

BACKGROUND

Since 1992, NASA and DRI have developed and refined the Manned Spacecraft and Crew Survivability (MSCSurv) computer code to determine the likelihood that an orbital debris penetration causes death of crew members at the "assembly complete" stage of the International

Space Station. MSCSurv is a Monte Carlo simulation that computes the probability of occurrence of crew loss from orbital debris penetration. Within the code, a penetration may cause one of seven possible failure modes:

- (1) Critical external equipment failure
- (2) Manned module critical cracking (or "unzipping")
- (3) Critical internal systemic equipment failure
- (4) Critical internal payload equipment failure
- (5) Crew hypoxia during escape or rescue
- (6) Fatal fragmentation injury to crew
- (7) Critical thrust from module hole causing high angular velocity (occurring only when key Guidance, Navigation, and Control [GN&C] equipment is damaged) and, thus, preventing safe escape vehicle (EV) departure

Note that several of the failure modes (for example, modes 1 through 4, and 7) cause severe damage to the station that may preclude re-occupation without extensive repair.

Based on these damage modes, the probability of no loss (PNL) of the station's crew due to impact by orbital debris particles may be computed using the equation

$$PNL = PNP^R \quad (1),$$

where PNP is the probability of no penetration. In equation (1), PNP is a function of particle flux, module surface area, exposure time, and shield ballistic limit, and is determined by NASA-JSC using the BUMPER code. R is a function of hypervelocity damage and crew and station-related parameters. As outlined below, R is calculated within the MSCSurv code using the seven failure modes. A more detailed description is given in Reference [1].

To calculate R , MSCSurv:

- (1) Randomly generates a large number of debris particles (size, velocity, and approach direction) based on selected NASA orbital debris environment models,
- (2) Selects a space station impact location for each particle generated, based on exposure of the station from this approach direction,
- (3) Determines which of these particles penetrates the station shields based on the interacting particle and shield parameters,
- (4) Predicts the resulting damage from each particle that penetrates the station,
- (5) Compares the predicted damage from the impact to critical levels required to induce

- loss of one or more crew members, considering the exposure of the crew members to these damage levels and their ability to escape from them, and
- (6) Quantifies R for each module and the module cluster taken as a whole, averaged over millions of simulated penetrations (billions of impacts).

To perform (3), MSCSurv uses the same empirical and analytical ballistic limit relations used by the BUMPER code to quantify the number of particles that will penetrate the spacecraft shields. Step (4) requires use of hypervelocity impact damage prediction equations to determine hole size, crack length, and depth of penetration into the interior of the module. While steps (3) and (4) are related closely to hypervelocity impact phenomenology, step (5) requires other assumptions regarding the capability of the station to tolerate damage as well as the reactions of the crew and their physical capability to withstand and escape harm. The details of MSCSurv Version 4.0 have been thoroughly documented in MSCSurv Version 4.0 User's Guide [2].

Once completed, these calculations determine an R factor prediction for each module based on the seven failure modes. By altering the input parameters regarding crew operations, internal arrangement of the ISS modules, and other design factors, the analyst can compare the safety of modes of ISS operation. This comparison points to changes that could be made to lower overall probability of crew loss.

ENVIRONMENT

Our analyses used the following general assumptions for the orbital debris environment:

Orbital debris environment model = ORDEM 96 (NASA-JSC)

Station orbital inclination = 51.6°

Station orbital altitude = 418 km

Year = 2003

Solar flux at 10.7 cm = 166 Janskys

Debris population growth factor, N = .20

Orbital debris particle density = 2.8 g/cm³

PHYSICAL MODEL AND BALLISTIC LIMIT RELATIONS

Johnson Space Center (JSC) provided the geometry model and ballistic limit relations used

for these analyses, which corresponds to the BUMPER model used for the Stage 12A analyses.

The ballistic limit relations associated with each of the external shield designs can be found in "ISS Meteoroid & Debris Integrated Threat Assessment #9 (ITA-9)" found in Reference [3].

DAMAGE MODELS

Once MSCSurv has established that a penetration has occurred, it calculates the size of the hole using one of two models: the Burch model or the Schonberg/Williamsen (S/W) model, Reference [4]. The S/W model is an empirical model based on data obtained by laboratory testing of station-specific shield configurations. It is used in all instances in which the actual shield parameters resemble the tested shield parameters within a 25% variance of standoff (distance between shielding materials) and within a 50% variance of rear wall thickness. The Burch model or Burch D90 damage equation is a generic hole-size prediction model developed in the 1960's for aluminum plates and is used for those shields where no S/W model is available.

Table 1 shows a predicted distribution of hole sizes within the manned modules following orbital debris penetration, as calculated by MSCSurv 6.0. Note that although the RSA modules receive more penetrations, the average penetration is smaller than that predicted for the NASA/ESA/NASDA (i.e., "NASA" type) modules. This is because the general design of the RSA module shields more easily allows penetrations by orbital debris than their NASA counterparts, due to shorter standoffs and thinner materials used. When holes occur, they are (on average) smaller in RSA modules than those allowed by the generally more robust shielding of the NASA module design.

MSCSurv calculates crack lengths in a fashion similar to that used to calculate hole sizes. It uses either an empirical Schonberg/Williamsen crack-size model (again, applied to shield types with less than a 25% variance in standoff and 50% variance in rear-wall thickness compared to tested configurations) or simply multiplies the hole size from the Burch model by a user-specified factor (a nominal value of 2 for the analyses presented in this report). Table 2 shows MSCSurv 6.0's predicted distribution of crack sizes within the manned modules following orbital debris penetration. Note that the average

predicted crack sizes on the RSA modules are smaller than those on the NASA/ESA/NASDA

modules (similar to the trends for hole sizes).

Table 1 Predicted Pressure Wall Hole Distribution for Manned Modules (for One Million Penetrations)

US Lab	139150	35.61	21.91	11.30	6.71	5.63	4.43	3.20	2.89	2.82	2.14	1.77	0.89	0.70
Node-1	109888	82.02	28.02	7.17	1.92	0.52	0.28	0.07	0.00	0.00	0.00	0.00	0.00	0.00
FGB	503709	9.75	37.51	5.49	47.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Service AFT	2741015	80.21	9.69	2.55	1.19	0.96	1.17	0.89	0.24	2.63	0.08	0.05	0.05	0.30
SPP-1	687245	59.58	40.19	0.20	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HPGC	50490	42.23	27.47	14.50	6.84	3.29	2.15	1.26	1.12	0.51	0.39	0.22	0.00	0.00
Airlock	30825	27.84	15.36	15.13	8.62	7.54	9.61	6.57	3.01	1.88	1.23	0.96	0.61	1.65
Docking Compartment	627269	30.05	68.85	0.72	0.35	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PMA-1	32672	46.65	33.64	13.67	6.58	0.37	0.04	0.03	0.02	0.00	0.00	0.00	0.00	0.00
PMA-2	42968	39.76	31.36	15.78	9.93	2.72	0.25	0.04	0.02	0.03	0.00	0.00	0.00	0.10
PMA-3	18323	42.76	29.76	14.90	8.03	2.99	0.83	0.23	0.03	0.09	0.01	0.04	0.07	0.26
Progress	2425301	86.56	5.34	4.51	2.83	0.55	0.08	0.03	0.02	0.02	0.01	0.01	0.01	0.02
Service FWD	82320	8.81	56.93	23.60	9.62	0.69	0.17	0.12	0.06	0.00	0.00	0.00	0.00	0.00
Soyuz	2508825	85.65	2.79	1.49	5.30	3.68	0.44	0.08	0.04	0.41	0.02	0.01	0.01	0.08

Table 2 Predicted Crack Size Distribution for Manned Modules (for One Million Penetrations)

US Lab	139150	26.53	16.37	9.31	7.40	6.23	5.85	4.79	3.60	2.79	2.47	2.42
Node-1	109888	43.08	27.78	10.77	6.24	4.36	2.96	2.17	0.89	0.49	0.31	0.19
FGB	503709	2.14	13.48	29.09	3.32	3.07	4.69	20.52	23.69	0.00	0.00	0.00
Service AFT	2741015	65.18	20.27	4.09	1.19	1.23	1.05	0.51	0.53	3.11	0.55	1.05
SPP-1	687245	15.47	71.11	12.94	0.36	0.08	0.04	0.00	0.00	0.00	0.00	0.00
HPGC	50490	26.44	19.42	11.49	8.50	7.10	4.77	3.60	2.46	2.23	1.52	1.60
Airlock	30825	17.59	9.38	6.19	7.54	8.44	6.02	4.77	4.03	4.35	5.17	7.12
Docking Compartment	627269	6.92	45.94	45.36	0.96	0.37	0.32	0.10	0.01	0.01	0.00	0.00
PMA-1	32672	37.32	24.03	12.34	7.91	6.67	5.79	3.22	1.58	0.81	0.23	0.06
PMA-2	42968	30.88	19.95	12.00	9.23	7.40	6.47	4.61	2.92	2.21	1.79	0.80
PMA-3	18323	31.71	20.56	11.79	8.64	6.97	5.95	3.99	2.63	1.77	1.35	0.70
Progress	2425301	83.65	3.70	3.30	2.31	2.51	2.77	1.03	0.44	0.13	0.05	0.02
Service FWD	82320	1.20	14.72	45.16	8.75	15.77	10.93	2.43	0.54	0.17	0.11	0.12
Soyuz	2508825	82.39	4.00	1.47	0.98	0.85	1.40	4.17	2.92	1.26	0.25	0.09

Critical Cracking

Manned module critical cracking (also called module "unzipping") is the rupture of a manned module caused by unstopped crack growth following a pressure wall penetration by orbital debris. Every manned module pressure wall design has a unique susceptibility to this failure mode that is measured by the pressure wall's critical crack length (i.e., the crack size that, if exceeded, would cause the wall to "unzip" or crack over a long enough distance to rupture the module). We calculate the critical crack length

for a module using a combination of design parameters, including pressure wall thickness, curvature, alloy, and state of stress. Note that each module may have several critical crack lengths, due to different rear wall curvatures and thicknesses in local areas of the module.

Critical External Equipment Penetration

MSCSurv checks one of three possible failure modes for external equipment.

First, the code decides whether or not the penetration causes an immediate detonation of the propellant within fuel tanks.

If detonation does not occur, the code calculates whether or not the pressurized propellant tanks or gas bottles “unzip”. We assume that unzipping of one of these elements causes crew loss through fragmentation or breach of the underlying pressure wall.

If an unzipping event does not occur, MSCSurv calculates whether a thrust from one of these external tanks causes the external tank to break away from the module. We assume this causes a catastrophic failure of the ISS by ripping a hole in the pressure wall.

Critical Internal Systemic Equipment

To perform these calculations accurately, we identified all Criticality 1 and integral (danger-producing) internal system elements aboard ISS manned modules. We then associated each of these internal systems with one or more external elements in the data files.

Critical Internal Payload Equipment

To perform these calculations accurately, danger producing internal payloads (such as high pressure containers) were identified and associated with one or more external elements in the data files, similar to the process used for Critical Internal Systemic Equipment.

Hypoxia

Hypoxia occurs when people pass out and die from lack of oxygen. To prevent deaths from hypoxia, the crew must seal off a leaking module or sector of the space station, or they must get into the escape vehicle and leave. In the event of a depressurizing leak, the crew's locations, responses, reaction times, movement rates, isolation methods, etc., are critical to saving themselves. Their responses can also be critical to saving the ISS.

Recognizing the criticality of crew response, we created a new crew response subroutine tailored to Stage 12A, using SSP 50506 as a guide.

In general, when the depressurization alarm sounds, the crew first moves to the Service Module for discussion and preliminary actions. Assuming no injury, they next move to the Soyuz where they perform a leak check. Provided the leak check confirms that the Soyuz is not leaking, the crew uses the current pressure and pressure rate readings to compute the time remaining until the cabin pressure reaches a

predetermined minimum value (“bail pressure”); this time is known as the “reserve time.” If the reserve time is at least 30 minutes, the crew re-enters the station and attempts to isolate the leaking module. If the reserve time is less than 30 minutes, they evacuate the station in the Soyuz.

Injuries necessitate specialized reactions to a penetration. MSCSurv treats injured crew members as stationary “objects” that must be rescued by the other crew members. The crew must find the injured crew member, stabilize him, and move him from the penetrated module, then isolate the module (if time permits). It is important to note that if a crew member is injured in this simulation, the rest of the crew will NEVER depart the station without him. An injured crewman is never abandoned.

A summary of some of the key assumptions affecting hypoxia for these analyses is given below:

- (1) The bail pressure is set for 510 mm Hg (9.859 psi) with a triangular variance of plus or minus 10%.
- (2) The critical pressure for the onset of hypoxia is 9.5 psi with no variance.
- (3) Onboard leak detectors take five minutes to give their first reading (with a uniform variance of plus or minus 20%). The five minutes begins once all crewmen arrive at the Soyuz. The detectors are assumed to be 50% reliable (with a uniform variance of $\pm 20\%$). In case the detectors do not work, the crew must follow with an ordered-hatch-closure protocol (time permitting).
- (4) No hatches are considered closed in normal operations.
- (5) A crew member can hear a hole larger than 2 centimeters (with a triangular variance of $\pm 50\%$), if he enters the penetrated module. If a crew member hears the hole, he stops and isolates the hole.

Fatal Injury

Fatal injury occurs when a crewman is struck by fragments of the penetrating particle or fragments of the pressure wall. In order for a fatal injury to occur, MSCSurv requires two conditions to be met:

The impacting particle must penetrate through racks or other internal equipment in its path.

A crewman must be located in close proximity to the site of penetration. We divided the entire

space station into crew stations, each about one meter wide along the cylindrical axis of the modules. When a penetration occurs, MSCSurv determines which crew station was penetrated. A crew member must be present in that station or a directly adjacent station in the same module for a fragmentation injury to occur.

EMERGENCY VEHICLE DEPARTURE

The crew departs from the station in the Soyuz when:

- (1) Bail pressure is reached before the hole is isolated,
- (2) Any crew injury occurs,
- (3) The critical module (Service Aft) depressurizes, or
- (4) Sealing off the depressurizing module would isolate the crew from the Soyuz if they stayed aboard (in Stage 12A analyses, this includes penetrations to the Service Forward and the Docking Compartment).

If one of the seven critical loss modes occurs, MSCSurv does not tally the occurrence of crew departure. However, MSCSurv will tally crew departure in cases of nonfatal injury, loss of control of station, and critical depressurization.

RESULTS

Table 3 shows the mean R factors computed by MSCSurv using baseline parameters and the ITA-9 assembly stage 12A configuration.

The overall mean R factor of 0.285 indicates that 28.5 percent of the time a penetration of the station by orbital debris results in one or more deaths. As discussed in a previous section, the NASA portion of the station tends to be tougher to penetrate but in the event of a penetration, the hole sizes and crack lengths tend to be larger—penetration depths tend to be larger as well. It is not surprising that MSCSurv predicts an R factor of 0.447 for the NASA side of the station and only 0.278 for the RSA side.

The overall R factor is determined by weighting each module's R factor by its overall likelihood of penetration. Since about 96% of all penetrations of the station occur on the RSA side, the RSA R factors drive the overall R factor. Hypoxia is by far the largest contributor to the R factor on both the RSA and NASA sides of the station. Critical external equipment penetrations and critical internal payload penetrations are the second and third leading contributors to the overall R factor. Much equipment data has been obtained and

incorporated into these analyses. Further data would improve the accuracy of the results.

Nonfatal injuries, late loss of station control and critical module depressurization are not counted in the total R factors but are presented in columns H, I, and J of Table 3. Column K shows the total occurrence of all ten events. This baseline run predicts that 57.4% of penetrations will result in one of these ten events.

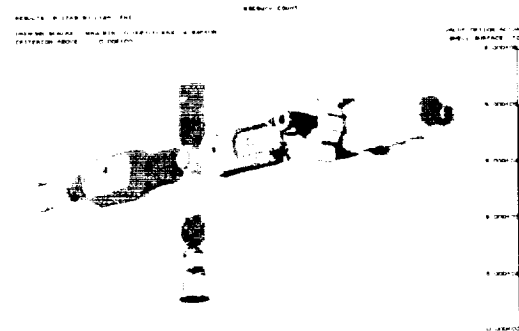


Figure 1 Number of Impacts per Element

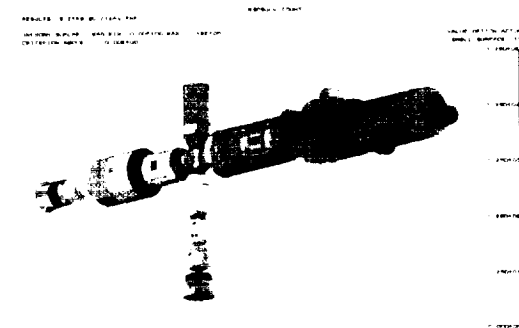


Figure 2 Numbers of Penetrations per Element

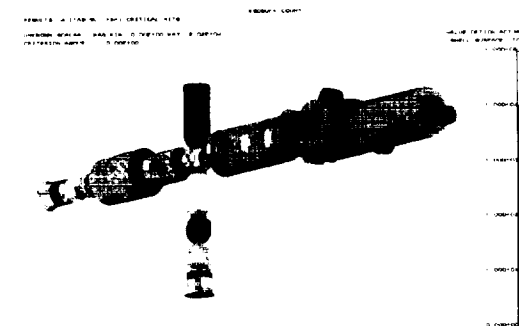


Figure 3 Numbers of Penetrations Leading to Crew Loss per Element

Table 3 Mean Probability of Station or Crew Loss Given an OD Penetration -- 12A

MODULE	RATIO=	A +	B +	C +	D +	E +	F +	G	H	I	J	K
(NASA)	0.447	0.046	0.007	0.039	0.031	0.295	0.029	0.000	0.021	0.000	0.163	0.631
(RSA)	0.278	0.001	0.068	0.011	0.034	0.157	0.005	0.001	0.094	0.018	0.181	0.572
STATION=	0.285	0.003	0.066	0.012	0.034	0.163	0.006	0.001	0.091	0.017	0.181	0.574

Legend for table headings

A = Critical cracking (unzipping)
B = External equipment penetration
C = Internal systemic equipment penetration
D = Internal experiment equipment penetration causes critical injury
E = Hypoxia loss
F = Fragmentation loss
G = Thrust induced angular velocity prevents departure from station
H = Fragmentation or secondary factors cause non-critical injury
I = Late loss of station control
J = Critical module depressurizes
K = Total of A-J.

the resulting R factors of these analyses, with the hypoxia contribution to R broken out separately. A total of six run types were performed:

- (1) Baseline
- (2) Bail pressure increased to 610 mm Hg – from the baseline value of 510 mm.
- (3) Bail pressure increased to 660 mm Hg.
- (4) Baseline AND Masks – Crew puts on oxygen masks after the depressurization alarm sounds. The mask is assumed to be functional for 20 minutes from the time a crew member dons it. The critical pressure while wearing the mask drops from 9.5 psi to 3.5 psi.
- (5) Bail pressure of 610 mm Hg AND masks
- (6) Bail pressure of 660 mm Hg AND masks.

SENSITIVITY STUDIES

In addition to analyzing the baseline case, we performed analyses to examine the effects of 1) utilizing oxygen masks, 2) increasing the bail pressure, and 3) combining the use of oxygen masks with higher bail pressures. Table 4 shows

The results of these runs show that hypoxia losses can be cut by more than half by using oxygen masks and a bail pressure of 610 mm Hg. The lowest R factors of all were obtained when oxygen masks and a bail pressure of 660 mm Hg were used.

Table 4 Comparisons of R Factors from Options to R Factors from Baseline

MODULE	Baseline (510 mm Bail Pressure) R	Baseline (510 mm Bail Pressure) Hypoxia R	610 mm Bail Pressure R	610 mm Bail Pressure Hypoxia R	660 mm Bail Pressure R	660 mm Bail Pressure Hypoxia R	Mask (510 mm Bail Pressure) R	Mask (510 mm Bail Pressure) Hypoxia R	610 mm Bail Pressure + Mask R	610 mm Bail Pressure + Mask Hypoxia R	660 mm Bail Pressure + Mask R	660 mm Bail Pressure + Mask Hypoxia R
(NASA)	0.447	0.295	0.434	0.285	0.420	0.263	0.279	0.111	0.288	0.119	0.281	0.114
(RSA)	0.287	0.157	0.227	0.109	0.212	0.088	0.216	0.092	0.191	0.063	0.180	0.068
STATION	0.285	0.163	0.236	0.117	0.221	0.096	0.219	0.092	0.195	0.066	0.185	0.060

**PREDICTIONS FOR OVERALL
PROBABILITY OF CREW LOSS FOR STAGE
12A**

The objective of this section of the report is to use the R factors in conjunction with the probability of no penetration (PNP) results obtained from BUMPER, in order to estimate the overall probability of no loss (PNL) for Stage 12A. As stated in the Introduction, the PNL is computed using the equation:

$$PNL = PNP^R$$

Table 5 shows a roll-up of predicted PNPs and their corresponding PNLs using the mean R factors calculated for Stage 12A. The PNPs for earlier stages were not broken out in the JSC report for ITA-9, so DRI performed the BUMPER run for Stage 12A used here.

Table 5 Predicted Probability of No Loss for Stage 12A

MODULE	PNP	R	$PNP^R = PNL$
(NASA)	0.9998213	0.447	0.9999201
(RSA)	0.9959365	0.278	0.99888687
STATION=	0.9957585	0.285	0.9987893

CONCLUSIONS

The Manned Spacecraft Crew Survivability computer program is a powerful analytical tool that enables ISS designers, managers, and safety specialists to estimate the probability of crew or spacecraft loss due to orbital debris impact. MSCSurv calculates the probability of crew loss following penetration of the space station by simulating millions of penetrations of the ISS manned modules and determining which penetrations lead to crew loss due to seven critical failure modes:

- Critical external equipment failure
- Manned module critical cracking (unzipping)
- Critical internal systemic equipment failure
- Critical internal payload equipment failure
- Hypoxia during escape or rescue
- Fatal fragmentation injury
- Thrust from module hole causing high angular velocity (occurring only when key GN&C equipment is damaged) and, thus, preventing safe EV departure.

During 2001, MSCSurv and the associated data files were extensively modified to accommodate changes in the space station shielding and geometry, crew operations, and internal/external

equipment configurations. We offer the following major conclusions regarding the results obtained thus far using MSCSurv and the ISS Stage 12A configuration:

- (1) Roughly 29% of all orbital debris penetrations lead to the death of one or more crew members at Stage 12A. This lethality rate could be significantly reduced through improved crew operations.
- (2) Using the values of R and PNP we predict the likelihood of death due to orbital debris penetration at Stage 12A to be between 0.09% and 0.18%, with a mean of 0.12%.
- (3) Modules with better shielding result in a lower overall probability of crew loss, even though their hole sizes (and R factors) are larger should a penetration occur.
- (4) Roughly 41% of the penetrations where all crewmen survive (which is 29% of all penetrations) will require the crew to depart from the space station in the Soyuz.
- (5) The largest contributors to the overall R factor are hypoxia (16%) and penetrations to external equipment (7%); 80% of the R factor can be attributed to one of these two critical failure modes. Improvements in crew protocols can significantly reduce hypoxia deaths. Higher fidelity input data for external equipment would greatly improve the accuracy of the overall analyses.

- (6) These predictions contain hole size and penetration depth equations that are large, continuing sources of uncertainty. NASA needs a better multi-plate penetration equation, effective to 15 km/sec for three or more spaced aluminum plates. This will drastically increase our confidence in these predictions.

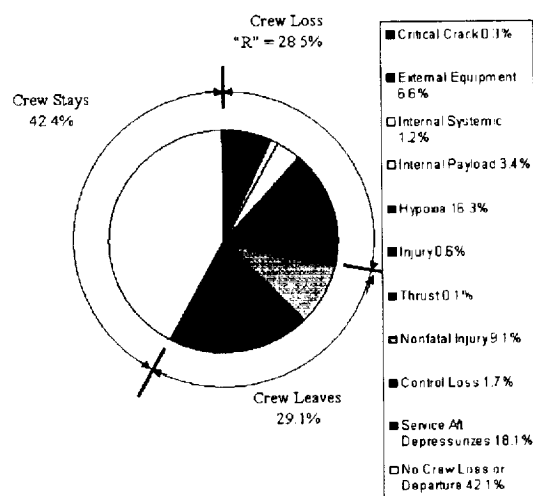


Figure 4 Assembly Stage 12A Configuration

FUTURE WORK

DRI will continue these analyses through at least this year in support of the International Space Station. Our goals are: (1) to improve the fidelity of the model, (2) to quantify and improve crew and space station survivability following orbital debris penetration by suggesting better procedures and improved internal module designs, and (3) to provide R factors for select earlier stage configurations. This Stage 12A assessment is the first R factor computation to be performed on a configuration preceding complete assembly.

RECOMMENDATIONS

We make the following recommendations based on findings from this and past assessments:

- (1) Change crew protocol to include use of oxygen masks.
 - Our trade study shows that using oxygen masks reduces hypoxia from 16% to 9% following orbital debris penetration.

- (2) Increase the bail pressure to 660 mm Hg.
 - The trade study shows that by using 660 mm Hg versus the baseline 510 mm Hg, hypoxia drops from 16% to 10%.
 - The trade study also shows that by using 660 mm Hg versus the baseline 510 mm Hg, crew departure rate increases from 29% to 40% following orbital debris penetration.
 - Further analyses to refine the optimum bail pressure using MSCSurv could prove useful.
- (3) Provide indication to crew as soon as possible as to the severity of the leak using improved leak detection and measuring equipment.

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